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SPECTRA-PHYSICS MODEL 944-1 LASER LEVEL, NOVEMBER 1976.(U)
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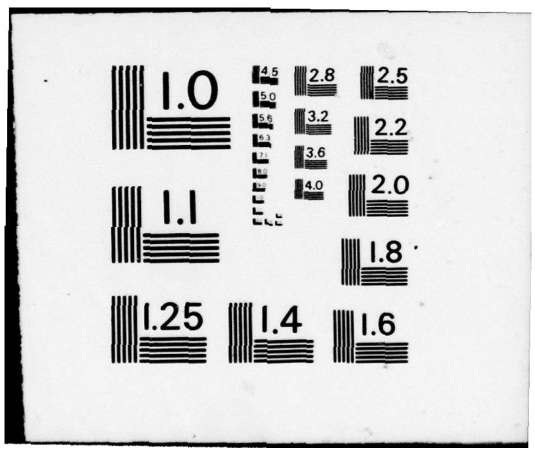
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NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0315-77
SPECTRA-PHYSICS MODEL 944-1 LASER LEVEL
NOVEMBER 1976

SERVING THE ARMY IN ITS PREVENTIVE MEDICINE PROGRAM

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
42-0315-77

2. GOVT ACCESSION NO. (6)

3. RECIPIENT'S CATALOG NUMBER
(14) USAEHA-42-0315-77

4. TITLE (and Subtitle)
(9) NONIONIZING RADIATION PROTECTION SPECIAL STUDY ~~NO. 42-0315-77~~, SPECTRA-PHYSICS MODEL 944-1 LASER LEVEL, NOVEMBER 1976.

5. TYPE OF REPORT & PERIOD COVERED
Special Study
November 1976

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
(10) Wesley J. Marshall

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
USA Environmental Hygiene Agency
Aberdeen Proving Ground, MD 21010

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Commander
USA Health Services Command
Fort Sam Houston, TX 78234

12. REPORT DATE
(11) 24 Jan 77

13. NUMBER OF PAGES
16
(12) 18p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Helium-Neon Laser
Optical Alignment Device

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
A laser radiation protection special study was performed on the Model 914-1 Laser Level. The laser was a Class IIIb system when the beam was stationary and such lasers present a momentary viewing hazard to the direct or specularly reflected beam. This laser did not present a hazard when operated in the scanning mode.

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DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010

HSE-RL/WP

24 JAN 1977

NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0315-77
SPECTRA-PHYSICS MODEL 944-1 LASER LEVEL
NOVEMBER 1976

ABSTRACT

A laser radiation protection special study was performed on the Model 914-1 Laser Level. The laser was a Class IIIb system when the beam was stationary and such lasers present a momentary viewing hazard to the direct or specularly reflected beam. This laser did not present a hazard when operated in the scanning mode.

It is recommended that the laser be operated in the scanning mode whenever possible, that a warning label be placed on the device, and that the beam be backstopped and the beam path be controlled when the device is operated in the stationary mode.

DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010

HSE-RL/WP

NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0315-77
SPECTRA-PHYSICS MODEL 944-1 LASER LEVEL
NOVEMBER 1976

1. AUTHORITY.

a. AR 40-5, Health and Environment, 25 September 1974.

b. Letter, PPO, Defense Mapping School, Fort Belvoir, VA, 20 August 1976, subject: Evaluation of Laser Equipment.

2. REFERENCES.

a. AR 10-5, Organization and Functions, Department of the Army, 1 April 1975.

b. AR 40-46, Control of Health Hazards from Lasers and Other High Intensity Optical Sources, 6 February 1974.

c. TB MED 279, Control of Hazards to Health from Laser Radiation, 30 May 1975.

3. PURPOSE. To evaluate the potential eye hazards associated with the use of the Spectra-Physics Model 944-1 Laser Level and to make recommendations designed to eliminate exposure of personnel to potentially hazardous optical radiation from this device.

4. GENERAL.

a. Background. This device is manufactured and distributed by Spectra-Physics, Inc., 1250 West Middlefield Road, Mountain View, CA. The device makes use of a helium-neon laser, a rotating mirror and a self-leveling mechanism. The instrument can be used either in the scanning mode or in the stationary mode. The rate of scan may be adjusted by dialing a knob. A leveling rod is usually used to locate the scanning beam. A detector moves up and down the rod until the beam is detected and the detector then marks the position of the beam. A photograph of the device is shown in Figure 1.

b. Inventory. Only one of these devices has been purchased by the Defense Mapping School at this time. This device was being considered for a standard issue item.

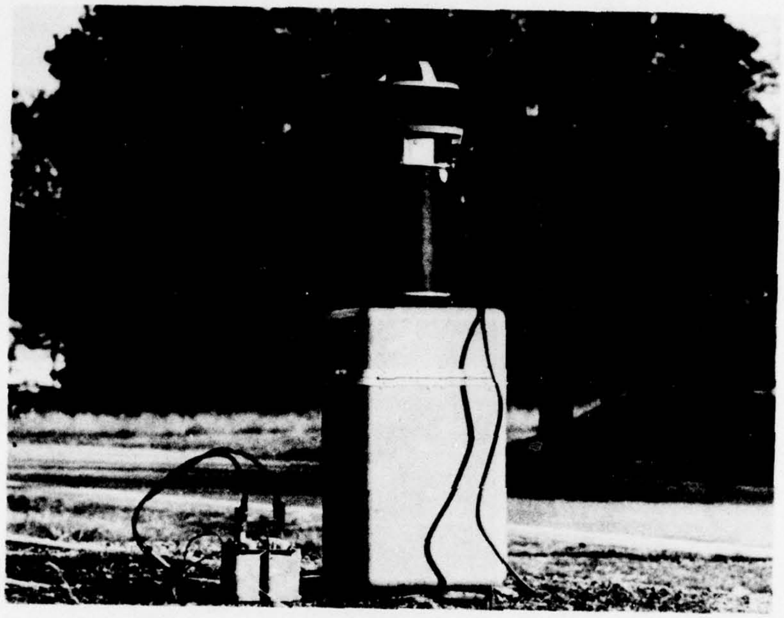

FIGURE 1. Photograph of the spectra physics model 944-1 laser level.

c. Instrumentation.

(1) EG&G Model 580 Radiometer System

(2) Calibrated Apertures

(3) Scientec Model 3600 Disk Calorimeter

d. USAEHA Measurements. Measurements were performed on one unit (Serial Number 3259 461) on 2-3 November at Building E2100, Aberdeen Proving Ground, MD.

e. Abbreviations and Units. A table of commonly used radiometric abbreviations and units is provided as Appendix A.

5. FINDINGS.

a. Measured Output Parameter.

(1) Power output: 2.5 mW

(2) Power output through apertures placed at the laser exit.

16 mm: 2.5 mW
10 mm: 2.2 mW
7 mm: 1.7 mW
5 mm: 0.91 mW
3 mm: 0.36 mW

(3) Wavelength: 632.8 nm (HeNe)

(4) Effective emergent beam diameter:

7 mm at 1/e-peak irradiance points

(5) Emergent beam divergence: 0.12 mrad with a minor focus (beam waist) at 29 m from the laser unit.

(6) Emergent beam Irradiance: 4.4 mW/cm^2 averaged over a 7-mm aperture

b. Beam Characteristics as a Function of Range. Beam irradiance measurements were taken at 0, 18 m, 30 m and 259 m. A theoretical plot of irradiance vs range is provided in Figure 2.

c. Warning label. A warning label was located on the device which stated the output power to be less than 5 mW and the words "Caution, Do Not Look Directly Into Laser Beam."

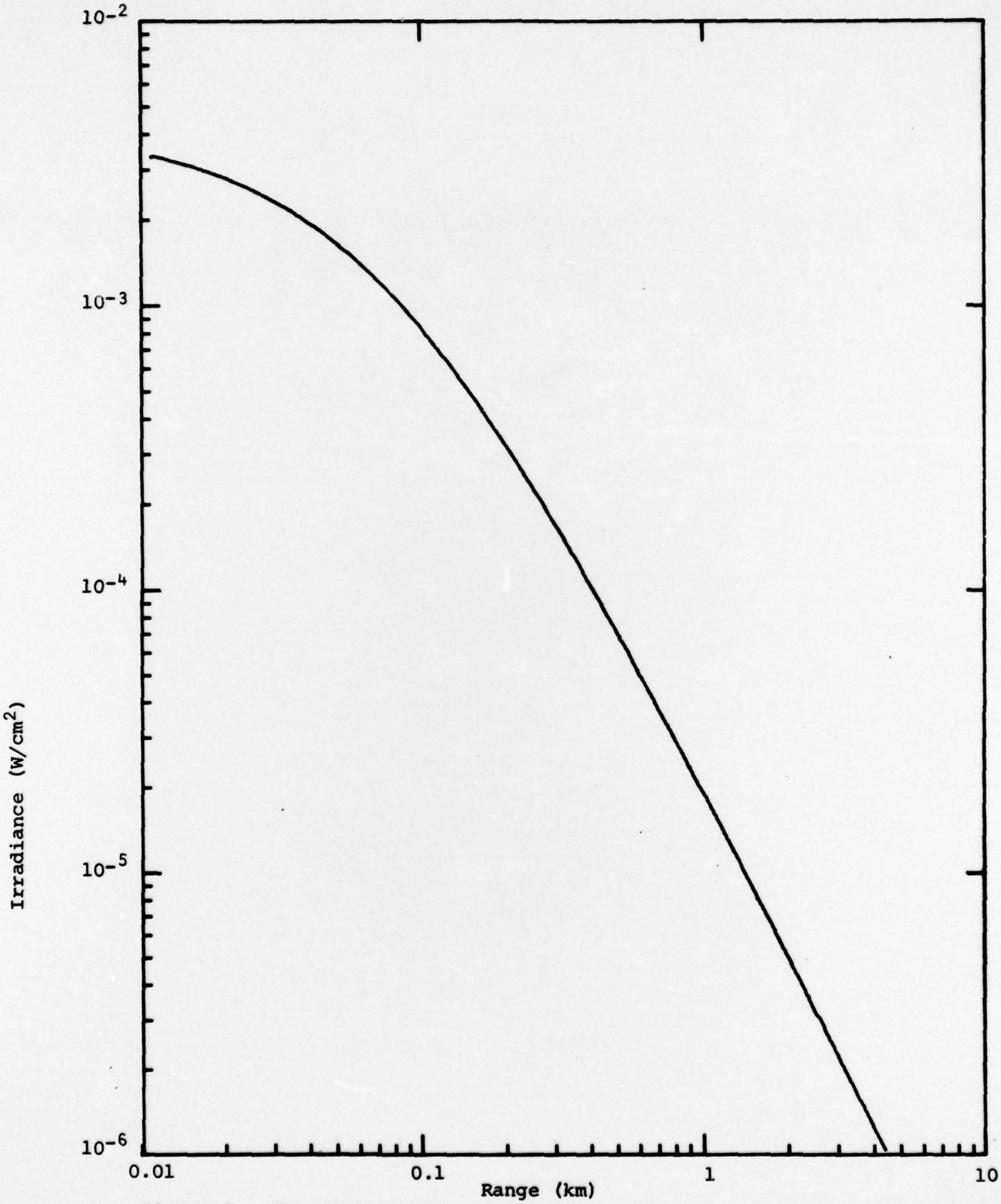

Figure 2. Theoretical Plot of Irradiance Through a 7-mm Aperture Versus Range for the Spectra Physics Model 944-1 Laser.

6. DISCUSSION.

a. Protection Standards. The protection standard for long-term (greater than 3 hours) staring into He-Ne lasers is 1.0 $\mu W/cm^2$. The protection standard for occasional accidental exposure to these lasers is 2.5 mW/cm^2 corresponding to 1 mW of power entering the eye. Accidental exposures are considered to be about 0.25 s in duration since a person will blink and will tend to look away from a bright light source. Shorter exposure durations have protection standards of higher powers depending on the duration of the exposure.

b. Hazard Classification. This laser is considered to be a Class IIIb or medium power laser since the total output power of the device in the stationary mode is between 1 mW and 500 mW. The device would be grouped into Class IIIa and need only a caution label rather than a danger label if its output power were reduced to 1 mW in a 7-mm aperture.

c. Stationary mode operation. This laser device presents the greatest potential hazard when the laser is operated in the stationary mode since it then presents a momentary (0.25 s) intrabeam viewing hazard at ranges less than 120 m from the laser exit.

d. Rotating mode. The maximum output irradiance measured through a 7-mm aperture for this device was 4.4 mW/cm^2 averaged over a 7-mm aperture (dark-adapted pupillary diameter). In order to meet current protection standards, the exposure duration to energy from this laser must be no more than 28 ms in any 0.25 s interval. A person at any distance from the laser outside of the protective enclosure could not be exposed in excess of 28 ms if the scanning rate of the device was set above 22 rpm. The closest point of access to the axis of rotation is 11 cm. However, if the laser output power were to increase to 5.0 mW (the maximum specified by the manufacturer), the permitted exposure duration in any 0.25 s would be 1.75 ms. In this case a person would receive an exposure exceeding protection standards at extremely close distances (5 cm from the outer housing) regardless of the scanning rate. However, a person located 1 m from the laser would be protected even from this increased power level at a scan rate of only 10 rpm. The hazard from this device decreases rapidly with distance when the unit is in the rotating mode. Appendixes B and C explain the formulas used in this evaluation.

7. CONCLUSION. This laser emits optical radiation which exceeds current protection standards. However, this device may be operated safely provided the operators are informed of the hazards and follow appropriate precautions. A slight reduction in output power would place it in Class IIIa.

8. *RECOMMENDATIONS*. *Follow* either alternative a or b:

a. Procure lasers with output powers less than 1 mW through a 7-mm aperture or require that the manufacturer install a filter of sufficient density (e.g., OD=0.5 at 632.8 nm) such that whenever the laser beam is not rotating at an angular rate exceeding 22 rpm, the filter falls into the beam path (para 5-38, AR 40-5).

b. Use the laser with existing characteristics under the following restrictions:

(1) Scanning mode. Operate the laser in the scanning mode with the scan rate set above 22 rpm whenever possible (para 1-4d, AR 40-46).

(2) Stationary mode. Follow these guidelines when using the laser in the stationary mode. [para 1-d(4), AR 40-46 and para 5-38b(5), AR 40-5].

(a) Backstop the beam at a distance where the entire beam path may be a controlled area (para 5-31, AR 40-5 and para 1-4d, AR 40-46).

(b) Keep the beam path at an elevation which will be either above or below normal eye level whenever possible [para 5-38b(5), AR 40-5].

(c) Post the area surrounding the beam path with warning signs similar to the one shown below [para 5-38, b(2), AR 40-5 and para 1-5d(4), AR 40-46].

(d) Replace the cautionary label on each device with a label similar to the following unless the units are modified with a 0.5 OD filter [para 1-5d(1), AR 40-46].

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APPENDIX A

USEFUL CIE RADIOMETRIC AND PHOTOMETRIC TERMS AND UNITS[1,2]

RADIOMETRIC				PHOTOMETRIC			
Term	Symbol	Defining Equation	SI Unit and Abbreviation	Term	Symbol	Defining Equation	SI Units and Abbreviation
Radiant Energy	Q_e		Joule (J)	Quantity of Light	Q_v	$Q_v = \int \Phi_v dt$	lumen-second (lm·s) (talbot)
Radiant Energy Density	W_e	$W_e = \frac{dQ_e}{dV}$	Joule per cubic meter ($J \cdot m^{-3}$)	Luminous Energy Density	W_v	$W_v = \frac{dQ_v}{dV}$	talbot per square meter ($lm \cdot s \cdot m^{-3}$)
Radiant Power (Radiant Flux)	Φ_e, P	$\Phi_e = \frac{dQ_e}{dt}$	Watt (W)	Luminous Flux	Φ_v	$\Phi_v = 680 \int \frac{d\Phi_e}{d\lambda} V(\lambda)\, d\lambda$	lumen (lm)
Radiant Exitance	M_e	$M_e = \frac{d\Phi_e}{dA} = \int L_e \cdot \cos\theta \cdot d\Omega$	Watt per square meter ($W \cdot m^{-2}$)	Luminous Exitance	M_v	$M_v = \frac{d\Phi_v}{dA} = \int L_v \cdot \cos\theta \cdot d\Omega$	lumen per square meter $lm \cdot m^{-2}$
Irradiance or Radiant Flux Density (Dose Rate in Photobiology)	E_e	$E_e = \frac{d\Phi_e}{dA}$	Watt per square meter ($W \cdot m^{-2}$)	Illuminance (luminous flux density)	E_v	$E_v = \frac{d\Phi_v}{dA}$	lumen per square meter ($lm \cdot m^{-2}$) lux (lx)
Radiant Intensity	I_e	$I_e = \frac{d\Phi_e}{d\Omega}$	Watt per steradian ($W \cdot sr^{-1}$)	Luminous Intensity (candlepower)	I_v	$I_v = \frac{d\Phi_v}{dr}$	lumen per steradian (lm·sr) or candela (cd)
Radiance	L_e	$L_e = \frac{d^2\Phi_e}{d\Omega \cdot dA \cdot \cos\theta}$ [5]	Watt per steradian and per square meter ($W \cdot sr^{-1} \cdot m^{-2}$)	Luminance	L_v	$L_v = \frac{d^2\Phi_e}{dr \cdot dA \cdot \cos\theta}$ [5]	candela per square meter ($cd \cdot m^{-1}$)
Radiant Exposure (Dose, in Photobiology)	H_e	$H_e = \frac{dQ_e}{dA}$	Joule per square meter ($J \cdot m^{-2}$)	Light Exposure	H_v	$H_v = \frac{dQ_v}{dA} = \int E_v dt$	lux-second (lx·s)
				Luminous Efficacy (of radiation)	K	$K = \frac{\Phi_v}{\Phi_e}$	lumen per watt ($lm \cdot W^{-1}$)
				Luminous Efficiency (of a broad band radiation)	V(•)	$V(\bullet) = \frac{K}{K_m} = \frac{K}{680}$	unitless
Radiant Efficiency [3] (of a source)	η_e	$\eta_e = \frac{P}{P_i}$	unitless	Luminous Efficacy[3] (of a source)	η_v	$\eta_v = \frac{\Phi_v}{P_i}$	lumen per watt ($lm \cdot W^{-1}$)
Optical Density [4]	D_e	$D_e = -\log_{10} \tau_e$	unitless	Optical Density[4]	D_v	$D_v = -\log_{10} \tau_v$	unitless
				Retinal Illuminance in Trolands	E_t	$E_t = \frac{L_v}{S_p}$	troland (td) = luminance in $cd \cdot m^{-2}$ times pupil area in mm^2

1. The units may be altered to refer to narrow spectral bands in which case the term is preceded by the word *spectral*, and the unit is then per wavelength interval and the symbol has a subscript λ. For example, spectral irradiance H_λ has units of $W \cdot m^{-2} \cdot m^{-1}$ or more often, $W \cdot cm^{-2} \cdot nm^{-1}$.

2. While the meter is the preferred unit of length, the centimeter is still the most commonly used unit of length for many of the above terms and the nm or µm are most commonly used to express wavelength.

3. P_i is electrical input power in watts.

4. τ is the transmission

5. At the source $L = \frac{dI}{dA \cdot \cos\theta}$ and at a receptor $L = \frac{dE}{d\Omega}$

APPENDIX B

DETERMINING A LASER BEAM DIAMETER AND DIVERGENCE TO EVALUATE POTENTIAL RADIATION HAZARDS

1. BACKGROUND. To assess potential health hazards to individuals from exposure to laser radiation requires an understanding of several topics:

a. The shape or profile of the laser beam intensity distribution.

b. How this profile changes as the beam traverses the atmosphere.

c. The defining aperture for the optical radiation protection standards.

2. GAUSSIAN BEAM. The beam profile at a fixed distance from a single-mode laser (often the case for gas lasers) closely resembles a Gaussian distribution. We can express this distribution mathematically for beam irradiance $E(r)$ as a function of radial distance r from the center axis of the beam by:

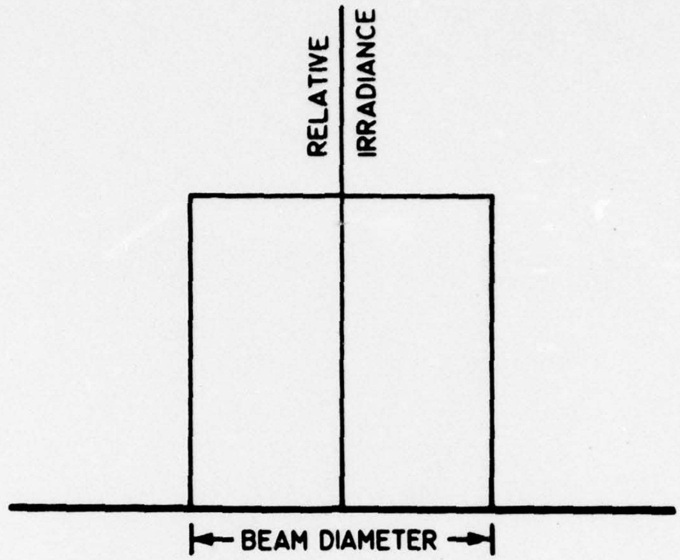
$$E(r) = E_o e^{-r^2/2\sigma^2} \tag{1}$$

where E_o is the peak irradiance and σ is a constant which is related to the width of the distribution. Normally, the radiant exposure beam profile at the exit of a solid-state pulsed ruby laser system such as from some laser rangefinders does not even remotely follow a Gaussian distribution. At great distances from the laser, however, the beam is "truncated" and broken up into various hot spots. This change in the shape of the beam occurs due to diffraction at the lasers projection optics as well as interactions between the beam and the atmosphere. Measurements of maximal beam irradiance at several points downrange permit the calculation of an effective beam diameter which can be related to σ. Hence, the mathematics of equation 1 could also be used for a pulsed laser system with beam radiant exposure $H(r)$ as a function of radial distance assuming an effective value for σ.

3. BEAM DIAMETER. The diameter of a laser beam is not directly apparent for a Gaussian distribution as opposed to a rectangular beam profile as shown in Figure 1. Laser technologists have defined the beam diameter in different ways. We wish to define the beam diameter such that the peak irradiance can be readily calculated. Consider the total power contained within a beam with radial symmetry. This total power, Φ, is given by the following integral:

$$\Phi = \int_0^\infty E(r)\ 2\pi r\ dr \tag{2}$$

where $2\pi r\ dr$ is the differential area of an infinite diameter circular aperture thru which the beam passes. Combining equations 1 and 2 and integrating we obtain:



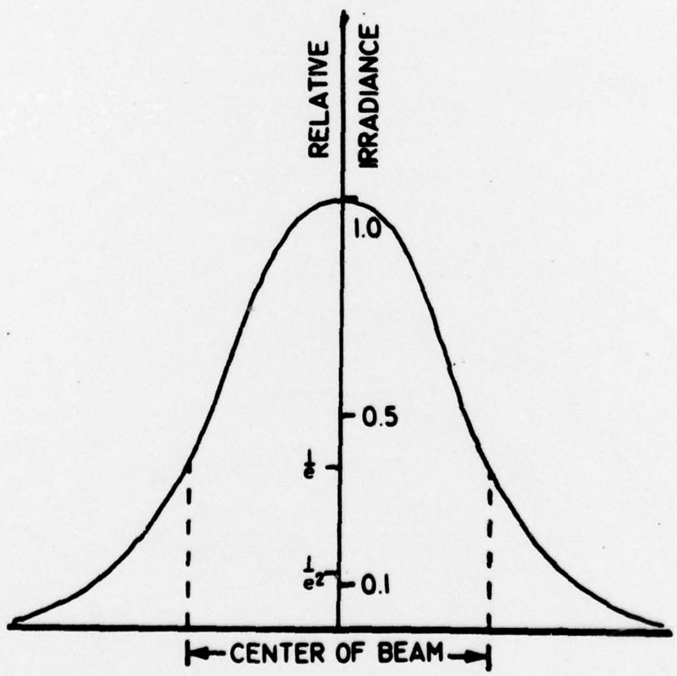


Figure 1. A Gaussian Beam as Illustrated in the Lower Graph has no Clearly Defined Edge as does the Rectangular Beam Profile Illustrated in the Upper Graph.

$$\Phi = \pi D_L^2 E_o/4 \text{ where } D_L \equiv 2\sqrt{2}\sigma \tag{3}$$

Physically D_L defines twice the radial distance to where the irradiance on the Gaussian distribution is reduced to E_o/e (or beam diameter to 1/e-peak-irradiance-points). Therefore by knowing the beam diameter defined at 1/e-peak-irradiance-points and the total power contained within the Gaussian profile it is possible to predict the peak irradiance with the same computation as for a rectangular beam. One simple method for experimentally measuring the beam diameter consists of allowing 63 percent or $1 - 1/e$ of the total beam power to pass thru an adjustable circular aperture located on the beam axis. The diameter of this aperture is D_L. (This can be mathematically verified by integrating equation 2 to the beam radius at 1/e-peak-irradiance-points or $r = \sqrt{2}\,\sigma$). Figure 2 is a plot of this integral over various limits of integration.

4. BEAM DIVERGENCE. The profile of this laser beam at any other point along its path will also be approximately Gaussian (assuming that other optical systems are not present which might obstruct the path or in any way modify the beam shape). The Gaussian beam in the far field will widen and the peak irradiance will be reduced as we travel farther from the laser. The total power within the beam will be reduced only slightly due to atmospheric absorption. The beam diameter at some distance, r, from the laser is given by

$$D_L = r \tan \phi + a \tag{4}$$

where ϕ is the beam divergence and a is the diameter to 1/e peak-irradiance-points at the laser output. Since most laser systems are highly collimated we obtain from equation 4:

$$D_L \simeq r\phi + a \tag{5}$$

From this expression it is apparent that the beam divergence must also be specified to 1/e-peak-irradiance-points. To demonstrate this consider specifying the beam diameter to $1/e^2$-peak-irradiance-points (D^1) then from equation 1 we can prove that:

$$D_L = D^1/\sqrt{2} \tag{6}$$

and equivalently:

$$a = a^1/\sqrt{2} \tag{7}$$

Therefore we find that:

$$\phi = \phi^1/\sqrt{2} \tag{8}$$

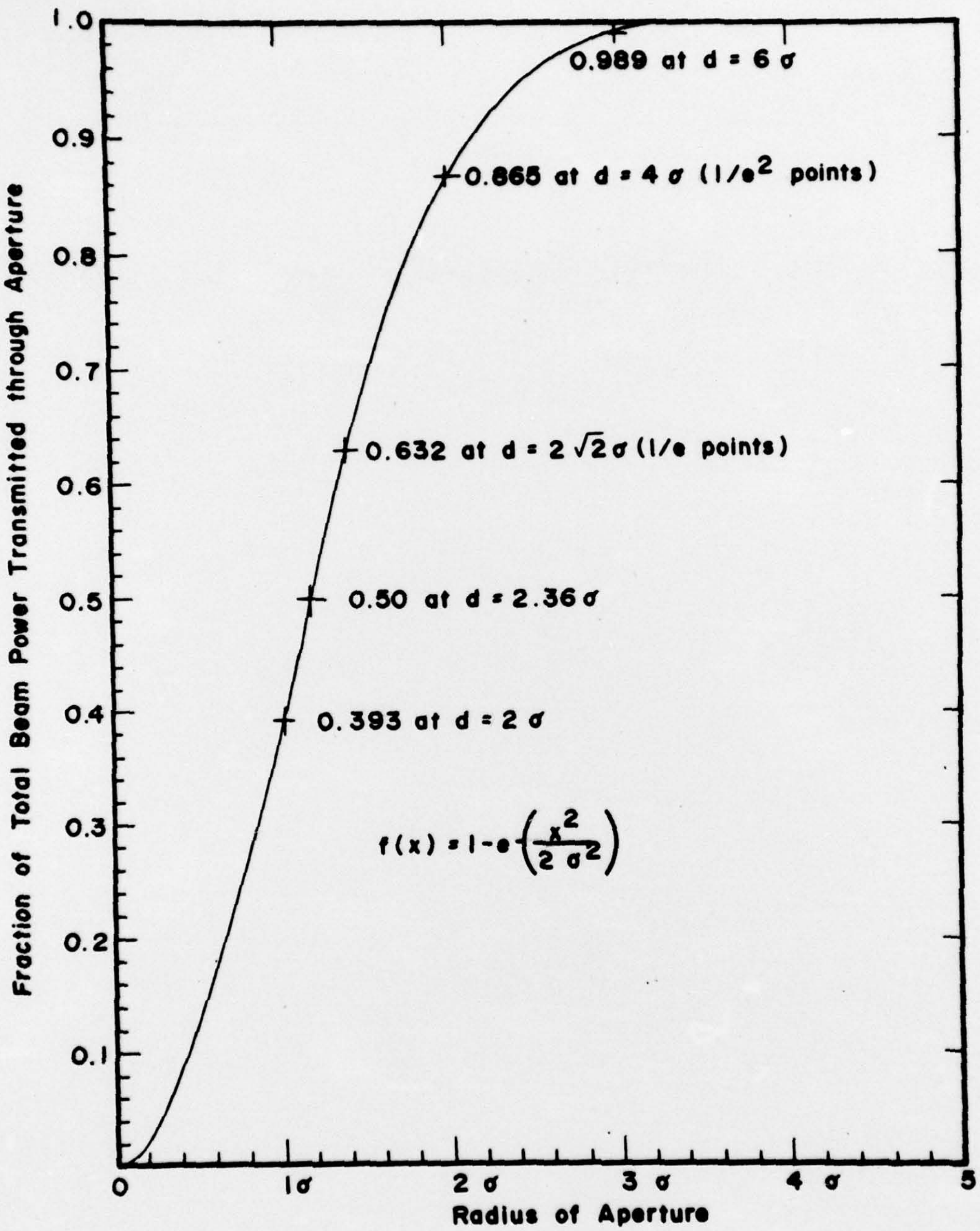


Figure 2. Beam Diameter is Determined by Measuring the Fraction of Total Power in a Gaussian Laser Beam which Passes through a Calibrated Aperture. If 63 Percent of the Beam Passes through an Aperture of Diameter, d, then d is the Diameter at 1/e Points. The Diameter at 1/e Points is 1.2 Times the Aperture that Passes 50 Percent of the Total Beam Power.

where a^1 and ϕ^1 are the exit beam diameter and divergence respectively defined to $1/e^2$-peak-irradiance.

The laser range equation is obtained by combining equations 3 and 5 or:

$$E(r) = (1.27\ \Phi\ e^{-\mu r})/(a + r\phi)^2 \tag{9}$$

where $e^{-\mu r}$ is the atmospheric transmission. (μ is called the atmospheric attenuation coefficient and is normally very small.) Hence, although beam divergence could be defined in several ways, it is convenient for a hazard evaluation to select the beam divergence defined at 1/e-peak-irradiance-points so that it is possible to predict the peak irradiance within a Gaussian profile at any distance from a laser of known output power. We can also apply this equation to experimentally measure the beam divergence. We can measure the peak irradiance with a detector whose sensitive diameter is much smaller than D_L for the beam in the far field of the laser ($r\phi \gg a$) and them compute ϕ from equation 9 since Φ, μ, r and a can also be measured.

5. PROTECTION STANDARDS. Why does one need to calculate the peak irradiance in the beam? We do not always need the peak irradiance but normally the beam diameter, D_L, is much larger than the sampling diameter for the laser protection standards since the potential hazard often extends to great distances from the laser. The protection standards for the skin and cornea and lens of the eye are based upon power or energy transmitted through a 1-mm aperture (for wavelengths between 10^5 and 10^6 nm this aperture becomes 10 mm) whereas the aperture for the "retinal hazard region" of the spectrum (400 to 1400 nm) is based upon a 7-mm aperture (dark adapted pupilary diameter). Actual range measurements are performed on laser systems with small exit beam diameters using an appropriate diameter aperture placed directly in front of the detector and centered on the beam axis.

6. RELATIVE BEAM POWER OR ENERGY. The maximum power or energy available to pass thru the appropriate defining aperture (for the various protection standards) is the most useful parameter to determine from the standpoint of evaluating optical radiation hazards. Figure 2 can be used to relate the fraction of total power transmitted thru different diameter apertures when the total beam power is known. Expressed mathematically Figure 2 simply states that the power thru an arbitrary axial aperture of diameter d is:

$$\Phi d = \Phi(1-\beta) \tag{10}$$

where $\beta = E(d/2)/E_o$ and $d = 2\sigma\sqrt{2\ln(1/\beta)}$.

By integrating the Gaussian profile over the area of an arbitrary circular aperture and combining this power with equation 3 we obtain another useful expression:

$$\Phi d = \Phi[1-e^{(d/D_L)^2}] \quad (11)$$

Hence a general laser range equation can be seen from equation 11 which could be applied to laser systems which have relatively short retinal hazardous ranges (D_L is of the same order of magnitude as 7 mm) or to telescopic viewing of such beams. The average irradiance over an arbitrary axial circular aperture of diameter d is given by:

$$E(r,d) = 2.6\Phi[1-e^{(d/D_L)^2}]e^{-\mu r} \quad (12)$$

This range equation is primarily applied to low power Ga-As laser diodes and He-Ne lasers.

APPENDIX C

DETERMINING HAZARDS FROM SCANNING LASER BEAMS

1. The total maximum radiant exposure H_e incident upon an observer's eye for a nominal dark-adapted pupillary diameter of 7 mm is the laser beam maximum irradiance E_e averaged over a 7-mm-diameter area multiplied by the exposure duration (t). Expressed mathematically this is:

$$H_e = E_e t \quad (1)$$

2. The radiant exposure protection standard, H_{ps}, for visible and near-infrared laser pulses lasting between 18 μs and 10 s is given by:

$$H_{ps} = 1.8 C_a t^{3/4} \text{ mJ/cm}^2 \quad (2)$$

Therefore, the maximum permissible exposure duration for pulses from this laser is:

$$t = [1.8 C_a / E_e]^4 \text{ for } 18\mu s \le t \le 10 s \quad (3)$$

where t represents the accumulated exposure duration in 0.25 s and C_a is a wavelength correction factor (C_A = 1 for $400 \le 2 \le 700$).

3. The minimum scanning rate, S, necessary to produce the necessary exposure duration as given by equation (3) for a scanning beam is given in the following equation:

$$S \ge (0.7)/rA\Theta s \text{ for } S < 4\text{Hz} \quad (4)$$

where e_s represents the maximal scanning angle in radiance (2π for a complete circle) and r represents the minimum viewing distance measured in cm from the axis of rotation.

4. If the scanning rate exceeds 4 in the equation (4) or the calculated rate exceeds the maximum of the device, the exposure time can not be reduced to the permitted value by increasing the scan rate. The minimum permissible viewing distance, r, may be calculated by equation (5) using a particular value for S (for values of S>4, use 4)

$$r = 0.7/St\Theta s \quad (5)$$

5. These formulas apply primarily to slowly scanning He-Ne or GaAs laser beams.